Indirect Search for Dark Matter with the ANTARES Neutrino Telescope

V. Bertin

Indirect Search of Dark Matter with the ANTARES Neutrino Telescope

V. Bertin[1] on behalf of the ANTARES Collaboration

[1]CPPM, Aix-Marseille Université, CNRS/IN2P3,
163 avenue de Luminy – Case 902, 13288 Marseille cedex 9, France

E-mail : bertin@cppm.in2p3.fr

Abstract. Indirect search for Dark Matter trapped inside celestial bodies is one of the main physics goals of neutrino telescopes. The expected flux coming from supersymmetric Dark Matter annihilations in the Sun and the sensitivity of the ANTARES and KM3NeT detectors to such a signal are presented. The ANTARES detector has been taking data during its construction phase in 2007 with five lines operational. This allowed to set a first limit on the neutrino flux coming from Dark Matter annihilations in the Sun with this experiment. A limit on Dark Matter to proton cross section in the framework of Minimal Universal Extra Dimension model is also presented.

1. Introduction

The most popular paradigm of modern cosmology considers the Dark Matter as a population of stable weakly interacting massive particles (WIMPs) relic from the Big Bang, although not yet discovered. Those particles would gravitationally accumulate in the core of massive celestial bodies such as stars or to a lesser extend planets as the Earth, where they could self-annihilate into ordinary matter and eventually produce significant high energy neutrino fluxes. Indirect search for Dark Matter looking at such neutrino fluxes coming from the core of the Sun, the Earth or the Galactic Centre is thus one of the main physics goals of the current and future neutrino telescopes.

2. The ANTARES neutrino telescope

The ANTARES detector [1] is the first undersea neutrino telescope and the largest one of the Northern hemisphere. It is composed of 12 mooring lines, each holding 75 photomultipliers distributed on 25 storeys (the titanium structure holding a triplet of photodetectors), installed at a depth of about 2500 metres off shore the Provençal coast of France, in order to form a 3D-matrix of ~900 photodetectors. The main goal of the experiment is to look for the Cherenkov light induced by high energy muons during their travel in the sea water throughout the detector. The trajectory of the muon track is reconstructed from the detection time of the Cherenkov photons as well as from the positions of the photodetectors. An indirect search for neutrinos can then be performed by selecting the upward-going muons produced by neutrinos which have passed through the entire planet and interacted in the vicinity of the detector. The direction of the incoming neutrino, being almost collinear with the secondary muon, can then be determined with an accuracy reaching 0.2° for high energy neutrinos above 10 TeV. Due to its size and the spacing of the photomultipliers, the ANTARES detector has a low energy threshold of ~20 GeV for reconstructed neutrinos and an effective area of $\sim 10^{-3}$ m² for neutrinos with an energy of 500 GeV. The effective area increases strongly with the neutrino energy and reaches ~1 m² for PeV energy neutrinos. Its location in the Northern hemisphere makes it complementary in sky coverage with the South Pole neutrino telescopes AMANDA and IceCube. In addition, a large fraction of the full sky can be observed with ANTARES thanks to the rotation of the Earth, including the central part of the Galaxy which is believed to be the host of many high energy phenomena.

Data taking with the ANTARES detector started after the undersea connection of the first line in February 2006 followed by the second line in September 2006. Three additional lines were connected in January 2007, and another five connected in December 2007. The apparatus reached its complete configuration with the last two lines being connected in May 2008. Some maintenance operations of the detector have successfully been carried out in 2009 and 2010. Line 12 was repaired and reconnected in 2009. Line 6 was repaired, redeployed and is currently waiting for the next submarine connection operation scheduled at the end of 2010, while Line 9 was recovered in Spring 2010 and is currently under repair.

In ANTARES data, event reconstruction is performed by a χ^2 fit of the photodetector hit times as a function of their positions assuming that the light originates from the Cherenkov cone of a muon track passing through the detector. Although the photomultipliers point at 45° downwards, the vast majority of reconstructed events are due to down-going atmospheric muons. These events may represent a background to the neutrino sample if badly reconstructed and not recognised as such. Within the Collaboration, extensive efforts have been carried out to develop efficient reconstruction methods, as well as to improve the Monte Carlo simulation of the detector. An illustration of the present situation is given in figure 1 showing the elevation angle of the reconstructed events from the data recorded in 2007 with a 5-line detector and in 2008 with a 9-to-12-line detector. A clear separation between the upward-going neutrino events and the down-going muon events is obtained as well as a good

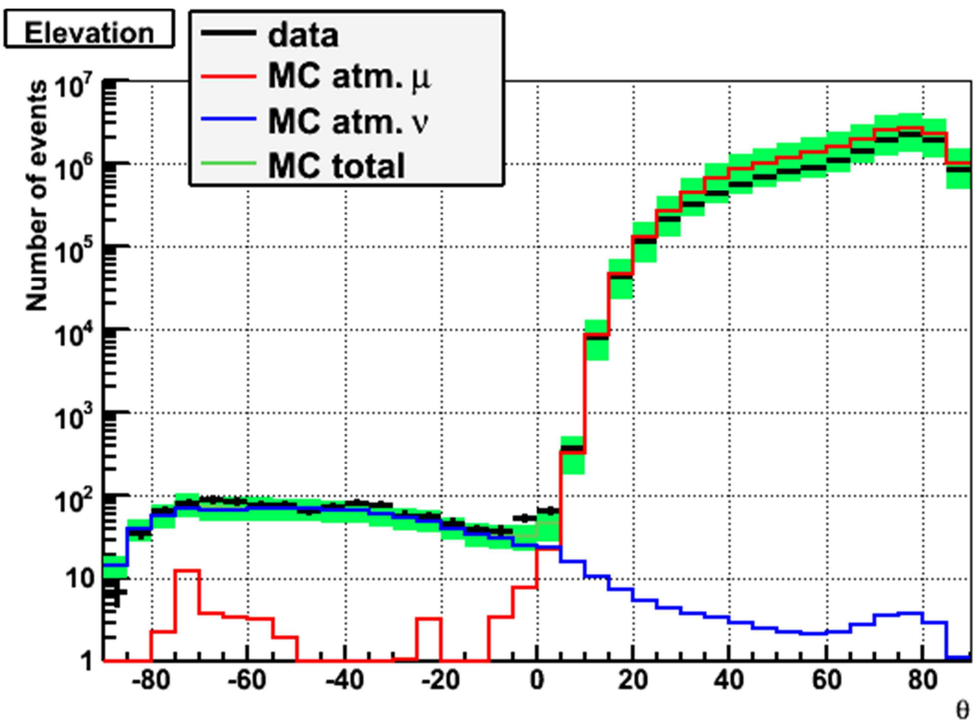

Figure 1. Elevation angle distribution of reconstructed events in data recorded in 2007 with a 5-line detector and in 2008 with a 9-to-12-line detector. The solid lines show the expected distribution for the atmospheric neutrino (blue) and atmospheric muon sample (red), while the green band shows the systematic uncertainty on the simulated total distribution.

agreement between the data sample and the simulated events. A total of more than 1000 neutrino candidate events is selected within this period, corresponding to 3.1 neutrino per day of data taking on average.

3. Sensitivity to neutralino annihilations in the Sun in CMSSM models

The supersymmetric extensions of the Standard Model provide a natural Dark Matter candidate in the form of the lightest neutralino, a particle composed of the supersymmetric partners of the neutral gauge and Higgs bosons. In models with conserved R-parity, the neutralino is a Majorana particle and a stable WIMP which for suitable choice of model parameters can have a relic density in agreement with the one derived from the WMAP measurements [2] of the Cosmic Microwave Background.

The signal of neutralino annihilations into the Sun has been studied within the context of the Constrained Supersymmetric Standard Model (CMSSM) scenario for which the neutralino properties depend on the four parameters m_0, $m_{1/2}$, A_0, tan(β) and sign(μ). From those parameters defined at the GUT energy scale, the properties of the supersymmetric particle spectrum including the neutralino at the electroweak scale are calculated using renormalization group equations (RGE). The expected neutrino flux resulting from neutralino annihilations into the Sun was calculated for approximately four million parameter sets with a modified version of DarkSUSY 4.1 [3] using a random walk method to scan the regions of the parameter space allowed by theoretical and experimental constraints and to highlight models predicting a neutralino relic density in agreement with the WMAP constraints. The RGE code ISASUGRA [4] was used for the calculation of the supersymmetric particle spectrum and the halo model of Navarro, Frenk and White [5] was assumed with a local Dark Matter density of

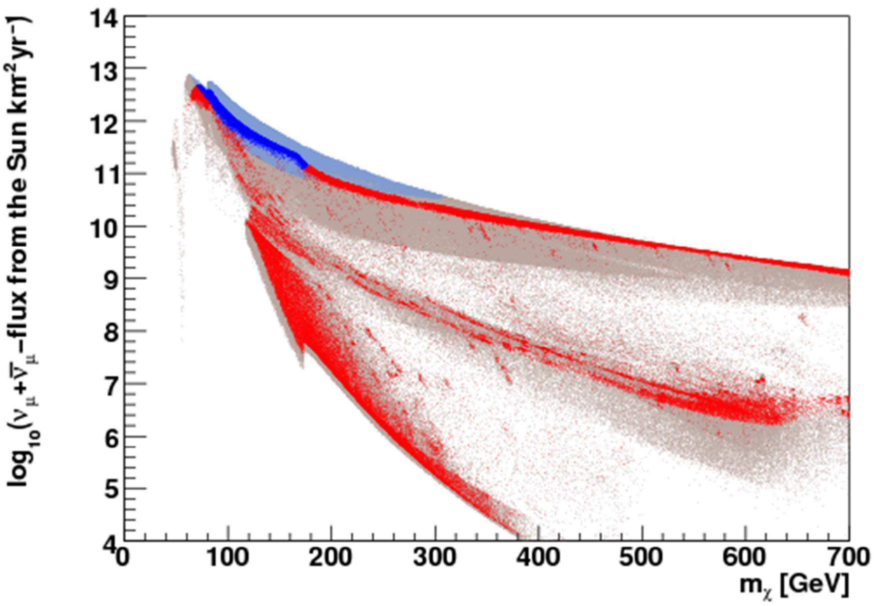

Figure 2. Sensitivity of ANTARES to neutrinos produced by annihilations of neutralinos into the Sun in CMSSM models. The flux of ν_μ and anti-ν_μ integrated for neutrino energies above 10 GeV is given as a function of the neutralino mass. Blue points indicate models within the sensitivity of ANTARES in 3 years, while red points show models outside the reach of this experiment. Brightly coloured points indicate models with a relic density predicted within 2σ of the WMAP region, shaded ones are those outside.

0.3 GeV/c² per cm^3. The flux calculation takes into account the effect of absorption and oscillations of neutrinos inside the Sun as well as during their propagation through vacuum from Sun to Earth.

Knowing the effective area of the ANTARES detector as a function of the neutrino energy, an estimated detection rate can then be calculated from the neutrino flux. Taking into account the irreducible background coming from atmospheric neutrinos as well as an additional background due to misreconstructed atmospheric muon events, a sensitivity is derived considering the signal and background events integrated within a cone of 3° radius around the direction of the Sun. Assuming that only the averaged background rate will be measured, an achievable upper limit for three years of data taking with the complete ANTARES detector can be derived and compared to the detection rate predicted for each individual CMSSM model. Figure 2 highlights the models which can be excluded by three years of data taking with the complete ANTARES detector. The sensitivity of ANTARES will allow to put constraints on part of the CMSSM parameter space, in particular in the so-called "Focus Point" region [6] where the neutralino is mainly of Higgsino type and for which higher neutrino fluxes and harder neutrino spectra are expected.

In order to compare this sensitivity with current limits or expected sensitivities published by other indirect detection experiments, it is more common to present it in term of muon flux at the detector. This quantity becomes however site dependent, being related to the neutrino propagation through the Earth and the target density around the detector. Figure 3 shows the corresponding neutrino induced muon flux integrated above an energy threshold of 1 GeV, which was calculated using neutrino-to-muon conversion rates extracted from DarkSUSY. Figure 3 (left) shows the expected sensitivity of ANTARES to CMSSM models in three years of data taking, while figure 3 (right) highlight the models which could be tested by KM3NeT [7], a next generation of km-scale neutrino telescope in the Mediterranean Sea, in ten years of operation. The expected sensitivity of the IceCube detector with its DeepCore extension [8] is also presented. It can be seen that these new generation neutrino telescope will be able to test almost entirely the "Focus Point" region of the CMSSM parameter space.

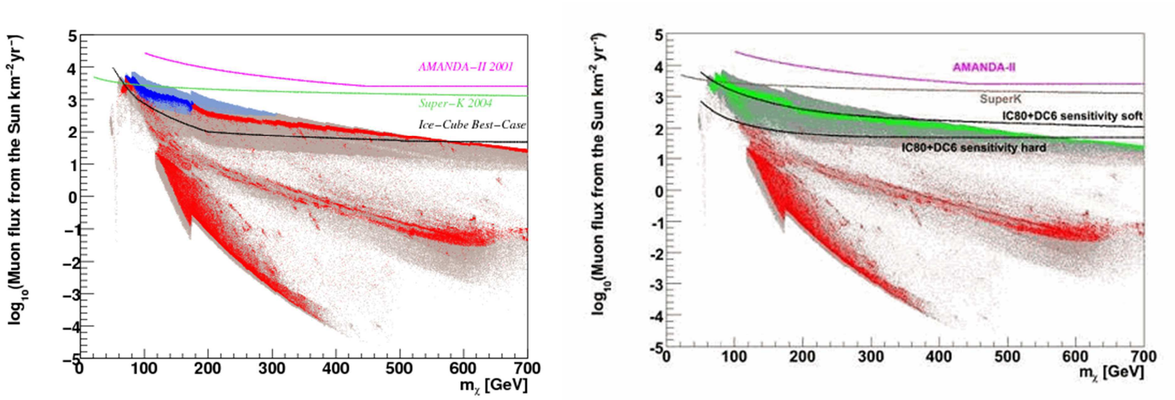

Figure 3. Sensitivity of ANTARES (left) and KM3NeT (right) to neutrino induced muons produced by annihilations of neutralinos into the Sun in CMSSM models. The muon flux integrated for energies above 1 GeV is given as a function of the neutralino mass. Blue and green points indicate models within the sensitivity of ANTARES (in 3 years) and KM3NeT (in 10 years) respectively, while red points show models outside the reach of both experiments. Brightly coloured points indicate models with a relic density predicted within 2σ of the WMAP region, shaded ones are those outside.

4. Limit on neutrino and muon flux from Dark Matter annihilations in the Sun with ANTARES

A search for neutrinos produced by Dark Matter annihilations into the Sun has been carried out in the data sample collected by the ANTARES detector during its five line operation phase in 2007. During this period, corresponding to 167 days of effective lifetime of data taking, more than 15 millions of muon events have been recorded. After reconstruction and selection cuts, essentially based on the quality of the track fit, a sample of about 200 upward-going events representing the neutrino candidates are selected. This total event rate as well as their zenith angle distribution is found to be in good agreement with expectations from the background of atmospheric neutrinos.

This sample of upward-going events has been used to look for a possible excess of neutrinos coming from the direction of the Sun. With the condition that the Sun has to be below the horizon, and taking into account some trigger dead-time, the effective lifetime of this search period reduces to 68.4 days. The analysis is performed by counting the number of observed events inside a search cone centred towards the direction of the Sun. The expected background, mainly due to atmospheric neutrino events, has been estimated as a function of the cone opening angle by Monte Carlo simulation. This has been found in very good agreement with an alternative estimation obtained with the data sample by randomizing the direction of the upward-going events. In the data sample recorded with the ANTARES 5-line detector, the distribution of events observed towards the direction of the Sun as a function of the cone opening angle is found to be in good agreement with background expectation. A limit on a possible excess of events as a function of the cone opening angle has then been derived following the unified approach method of Feldman and Cousins [9].

Using the two extreme cases of a hard and a soft neutrino spectrum resulting from neutralino annihilations into W^+W^-/ZZ gauge bosons and b anti-b quarks respectively, an optimal cone size has been derived for every neutralino mass before analyzing the data. This allowed to set a limit on the flux of neutrinos, integrated above an energy threshold of 10 GeV, produced by neutralino annihilations inside the Sun as a function of the neutralino mass for these two hard and soft spectra, as shown in figure 4 (left). In order to compare this result with the limits published by other indirect detection experiments, the corresponding neutrino induced muon flux integrated above an energy threshold of 1 GeV was calculated. The limits obtained on that quantity are presented in figure 4 (right). Although they are not yet competitive, the limits obtained by ANTARES based on a data sample of about six months recorded with half of its final detector design are already promising.

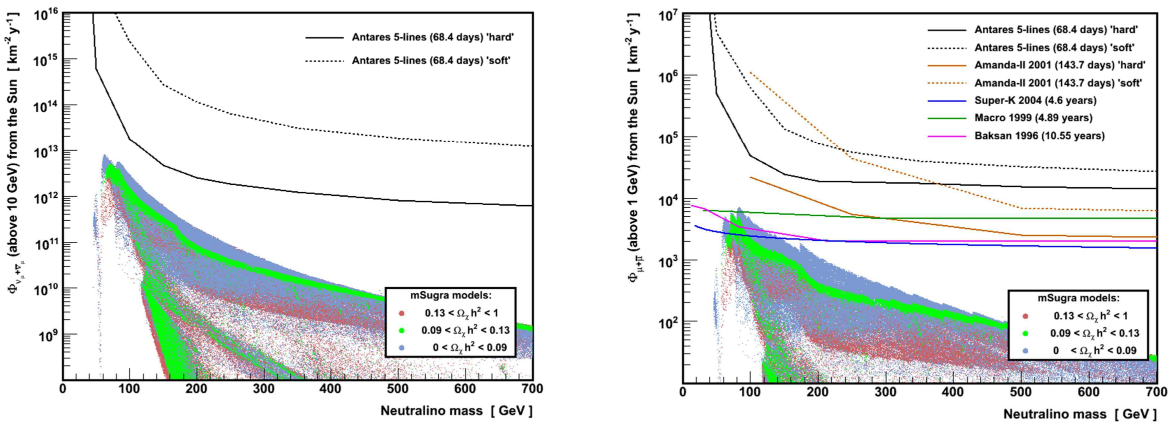

Figure 4. Limit on neutrino flux (Eν > 10 GeV) (left) and neutrino induced muon flux (Eμ > 1 GeV) (right) coming from the Sun obtained by ANTARES with the data of the 5-line period in comparison to the expected flux from neutralino annihilations in CMSSM models. Existing limits from other experiments are also shown. Green points indicate models with a relic density within 2σ of the WMAP region, blue and red points show models predicting respectively a lower or larger relic density.

5. Limit in the Minimal Universal Extra Dimension Framework

The same analysis result can also be interpreted in other alternative Dark Matter scenario in order to put some constraints on their parameter space. Another popular phenomenology is given by the Minimal Universal Extra Dimension (MUED) model with one extra-dimension, in which the first Kaluza-Klein (KK) excitation of the hypercharge gauge boson $B^{(1)}$ is the Lightest KK particle (LKP) and a viable Dark Matter candidate [10]. This model provides a highly predictive phenomenology with mainly two free parameters: the LKP mass M_B^1 and the relative mass splitting between the LKP and the first quark excitation $\Delta = (M_Q^1 - M_B^1)/M_B^1$. Accelerator measurements constraint the lower band for the LKP mass at 300 GeV [11]. The upper band is limited to a few TeV in order not to exceed the observed relic density and overclose the Universe. Figure 5 shows the upper limit on the LKP-to-proton cross section, governing the LKP capture within the Sun, which can be derived from the absence of high energy neutrinos coming from the direction of the Sun within the data recorded by ANTARES in 2007 with a 5-line detector. Although MUED models with a LKP relic density compatible with the WMAP constraints are beyond the reach of existing neutrino telescope, its illustrates the much higher sensitivity of such detectors with respect to direct detection experiments.

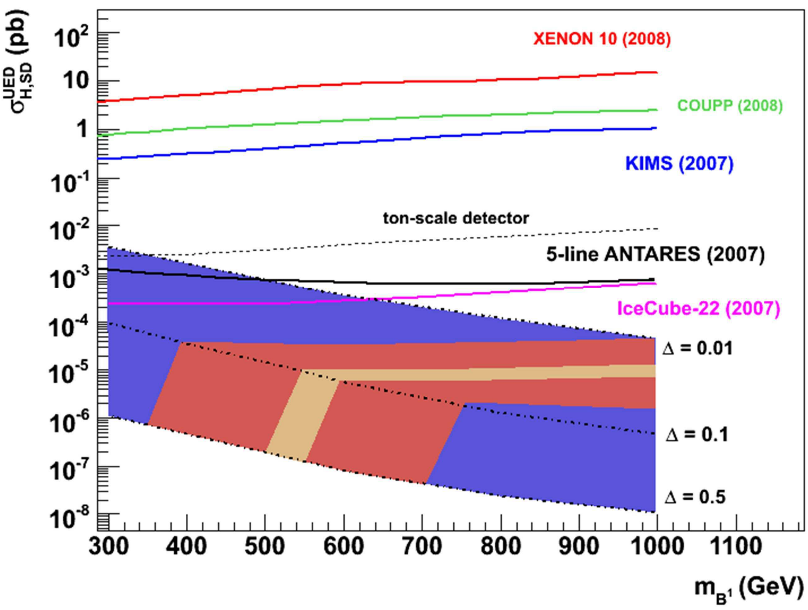

Figure 5. Limit on the LKP-to-proton cross section as a function of the mass of the LKP $B^{(1)}$ particle obtained from the search of neutrino events produced by Dark Matter annihilation inside the Sun in the data recorded by ANTARES in 2007 with a 5-line detector, compared to existing limit from other direct and indirect detection experiments. The light pink (resp. dark pink) region indicates MUED models with a LKP relic density within 1σ of the WMAP region (resp. within $0.05 < \Omega_{LKP} h^2 < 0.20$). The blue area indicates other MUED models.

6. Conclusion and perspectives

The ANTARES detector is the first undersea neutrino telescope and the largest one in the Northern hemisphere. A sample of about 200 neutrino events has been recorded during the building stage of the experiment in 2007, when five lines were operational. This set of events is found to be in good agreement with the expected atmospheric neutrino background. In particular, no excess has been found towards the direction of the Sun allowing to set a promising limit on the flux of neutrinos produced by Dark Matter annihilations inside the Sun. A similar analysis looking for signals of Dark

Matter annihilations in the Earth or towards the centre of the Galaxy is currently under progress, while more than 2000 neutrino candidates have already been recorded by ANTARES up to 2010.

Further studies of supersymmetric models show that the ANTARES experiment and a future km-scale undersea neutrino telescope KM3NeT will be sensitive to neutrino fluxes predicted by an interesting class of models for which the Dark Matter relic density is in agreement with current cosmological constraints.

References

[1] A. Aguilar *et al.* (ANTARES Collaboration), "ANTARES, the first undersea neutrino telescope", to appear in *Nuclear Instruments & Methods*, arXiv:1104.1607v2

[2] J. Dunkley *et al.*, *Astrophys. J. Suppl.* **180**, 306 (2009).

[3] P. Gondolo *et al.*, *JCAP* **0407**, 008 (2004).

[4] F.E. Page, S.D. Protopescu, H. Baer and X. Tata, "Isajet 7.69: A Monte Carlo generator for p p, anti-p p and e+e- reactions", hep/ph0312045 (2003).

[5] J.F. Navarro, C.S. Frenk and S.D.M. White, *Astrophys. J.* **490**, 493 (1997).

[6] J.L. Feng, K.T. Matchev and T. Moroi, *Phys. Rev. D* **61**, 075005 (2000).

[7] "Technical Design Report of the KM3NeT detector", http://www.km3net.org/public.php

[8] E. Resconi for the IceCube Coll., Nucl. *Instr. Meth. A* **602**, 7 (2009).

[9] G.L. Feldman and R.D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).

[10] G. Servant and T.M.P. Tait, *Nucl. Phys. B* **650**, 391 (2003).

[11] J.F. Oliver *et al.*, *Phys. Rev. D* **67**, 056002 (2003).